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Coordinated Multiwavelength Observations of BL Lacertae in 2000

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ABSTRACT

BL Lacertae was the target of an extensive multiwavelength monitoring campaign in the second half of 2000. Simultaneous or quasi-simultaneous observations were taken at radio (UMRAO and Metsähovi) and optical(WEBT collaboration) frequencies, in X-rays (BeppoSAX and RXTE), and at VHE gamma-rays (HEGRA). The WEBT optical campaign achieved an unprecedented time coverage, virtually continuous over several 10 – 20 hour segments. It revealed intraday variability on time scales of ~ 1.5 hours and evidence for spectral hardening associated with increasing optical flux. During the campaign, BL Lacertae underwent a major transition from a rather quiescent state prior to September 2000, to a flaring state for the rest of the year. This was also evident in the X-ray activity of the source. BeppoSAX observations on July 26/27 revealed a rather low X-ray flux and a hard spectrum, while a BeppoSAX pointing on Oct. 31 – Nov. 2, 2000, indicated significant variability on time scales of $\lesssim$ a few hours, and provided evidence for the synchrotron spectrum extending out to ~ 10 keV during that time. During the July 26/27 observation, there is a tantalizing, though not statistically significant, indication of a time delay of $\sim 4 - 5$ hr between the *Beppo*SAX and the R-band light curve. Also, a low-significance detection of a time delay of 15 d between the 14.5 GHz and the 22 GHz radio light curves is reported. Several independent methods to estimate the co-moving magnetic field in the source are presented, suggesting a value of $\sim 2\, e_B^{2/7}$ G, where e_B is the magnetic-field equipartition factor w.r.t. the electron energy density in the jet.

Subject headings: galaxies: active — BL Lacertae objects: individual (BL Lacertae) — gamma-rays: theory — radiation mechanisms: non-thermal

1. Introduction

BL Lacertae (= 1ES 2200+420; z = 0.069) was historically the prototype of the BL Lac class of active galactic nuclei (AGN). These objects are characterized by continuum properties similar to those of flat-spectrum radio quasars (non-thermal optical continuum, high degree of linear polarization, rapid variability at all wavelengths, radio jets with individual components often exhibiting apparent superluminal motion), but do usually show only weak emission or absorption lines (with equivalent width in the rest-frame of the host galaxy of < 5 Å), if any. In BL Lacertae itself, however, Hα (and Hβ) emission lines have been detected during a period of several weeks in 1995 (Vermeulen et al. 1995; Corbett et al. 1996), and in 1997

(Corbett et al. 2000). Superluminal motion of $\beta_{\rm app}$ up to $(5.0 \pm 0.2)\, h^{-1} \approx (7.1 \pm 0.3)$ has been observed in this object (Denn et al. 2000).

BL Lac objects and flat spectrum radio quasars (FSRQs) are commonly unified in the AGN class of blazars. Sixty-five blazars have been detected and identified with high confidence in high energy (> 100 MeV) gamma-rays by the EGRET instrument on board the *Compton Gamma-Ray Observatory* (Hartman et al. 1999; Mattox et al. 2001). To date, 6 blazars have been detected at very high energies (> 300 GeV) with ground-based air Čerenkov detectors (Punch et al. 1992; Quinn et al. 1996; Catanese et al. 1998; Chadwick et al. 1999; Aharonian et al. 2002; Horan et al. 2002; Holder et al. 2003). All of these belong to the sub-class of high-frequency peaked BL Lac objects (HBLs). The field of extragalactic GeV – TeV astronomy is currently one of the most rapidly expanding research areas in astrophysics. The steadily improving flux sensitivities of the new generation of air Čerenkov telescope arrays and their decreasing energy thresholds (for a recent review see, e.g., Weekes et al. 2002), provides a growing potential to extend their extragalactic-source list towards intermediate and even low-frequency peaked BL Lac objects (LBLs) with lower νF_ν peak frequencies in their broadband spectral energy distributions (SEDs). Detection of such objects at energies $\sim 40 - 100$ GeV might provide an opportunity to probe the intrinsic high-energy cutoff of their SEDs since at those energies, $\gamma\gamma$ absorption due to the intergalactic infrared background is still expected to be negligible at redshifts of $z \lesssim 0.2$ (de Jager & Stecker 2002). There has even been a claimed detection of BL Lacertae in 1998 with the Čerenkov telescope of the Crimean Astrophysical Observatory (Neshpor et al. 2001); however, this detection could not be confirmed by any other group so far (e.g., Aharonian et al. 2000).

BL Lacertae is classified as an LBL. From an interpolation between the GHz radio spectrum and the IR - optical spectrum, it can be inferred that its low-frequency spectral component typically peaks at mm to μm wavelengths, while the high-frequency component seems to peak in the multi-MeV – GeV energy range. BL Lacertae has been the target of many radio, optical, X-ray, and γ-ray observations in the past, and has been studied in detail during various intensive multiwavelength campaigns (e.g. Bloom et al. 1997; Sambruna et al. 1999; Madejski et al. 1999; Ravasio et al. 2002; Villata et al. 2003). It is a particularly interesting object for detailed X-ray studies: this is the region of the electromagnetic spectrum where the two broad components of the multiwavelength SEDs of BL Lacertae (and other LBLs) are overlapping and intersecting. X-ray observations of this source at different epochs show significant flux and spectral variability, indicating that the X-ray emission is at times dominated by the high-energy end of the synchrotron emission, while at other occasions it is dominated by the low-frequency portion of the high-energy bump of the SED. In fact, BL Lacertae has repeatedly shown a concave shape (e.g., Madejski et al. 1999; Ravasio et

al. 2002), with rapid variability mainly restricted to the low-energy excess portion of the spectrum (e.g., Ravasio et al. 2002, 2003).

In the framework of relativistic jet models, the low-frequency (radio – optical/UV) emission from blazars is interpreted as synchrotron emission from nonthermal electrons in a relativistic jet. The high-frequency (X-ray – γ-ray) emission could either be produced via Compton upscattering of low frequency radiation by the same electrons responsible for the synchrotron emission (leptonic jet models; for a recent review see, e.g., Böttcher 2002), or due to hadronic processes initiated by relativistic protons co-accelerated with the electrons (hadronic models, for a recent discussion see, e.g., Mücke & Protheroe 2001; Mücke et al. 2003).

While simultaneous broadband spectra are very useful to constrain blazar jet models, there still remain severe ambiguities in their interpretation w.r.t. the dominant electron cooling, injection, and acceleration mechanisms, as very drastically illustrated for the case of W Comae by Böttcher et al. (2002). Those authors have also demonstrated that a combination of broadband spectra with timing and spectral variability information, in tandem with time-dependent model simulations (e.g., Böttcher & Chiang 2002; Krawczynski et al. 2002) can help to break some of these degeneracies. For this reason, we organized an intensive multiwavelength campaign to observe BL Lacertae in the second half of 2000 at as many frequencies as possible, putting special emphasis on detailed variability information. In §2, we describe the observations carried out during the campaign and present light curves in the various energy bands. The diverse spectral variability patterns are discussed in §3, and the results of our search for inter-band cross-correlations and time lags are presented in §4. The source underwent a dramatic state transition from a rather quiescent state until mid-September 2000, to a very active state which lasted throughout the remainder of the year. We have obtained two detailed simultaneous broadband spectra of BL Lacertae, one before and one after this transition. The resulting SEDs are presented in §5. In §6 we use our results to derive estimates of generic model parameters, in particular of the co-moving magnetic field, independent of the details of any specific model. In a companion paper (Böttcher & Reimer 2003, in preparation), we will use leptonic and hadronic models used to fit the spectra and variability patterns found in this campaign. We summarize in §7.

Throughout this paper, we refer to α as the energy spectral index, F_ν [Jy] $\propto \nu^{-\alpha}$. A cosmology with $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ and $H_0 = 70$ km s^{-1} Mpc^{-1} is used.

2. Observations, data reduction, and light curves

BL Lacertae was observed in a co-ordinated multiwavelength campaign at radio, optical, X-ray, and VHE γ-ray energies during the period mid-May 2000, until the end of the year. The overall timeline of the campaign, along with the measured long-term light curves at radio, optical, and X-ray frequencies, is illustrated in Fig. 1.

2.1. Radio observations

At radio frequencies, the object was monitored using the University of Michigan Radio Astronomy Observatory (UMRAO) 26 m telescope, at 4.8, 8, and 14.5 GHz, and the 14 m Metsähovi Radio Telescope of Helsinki University of Technology, at 22 and 37 GHz. The radio light curves are shown in the top two panels of Fig. 1. At the lower frequencies (4.8, 8, and 14.5 GHz), they show evidence for flux variability on a ~ 30 % level on time scales of ~ 1 month and track each other closely. Superimposed on the large-amplitude variability on a ~ 1 month time scale, the 4.8-GHz and 8-GHz radio light curves exhibit low-amplitude variability on time scales of a few days. The discrete autocorrelation functions (Edelson & Krolik 1988) of these light curves indicate a sharp decline on a time scale of ~ 4 days.

The higher-frequency radio light curves indicate more erratic variability, with flux variations of ~ 25 % within a few days. However, those variability patterns are clearly undersampled in our data set, so that a more detailed analysis might not be meaningful at this point.

2.2. Optical observations

Focusing on an originally planned core campaign period of July 17 – Aug. 11, BL Lacertae was the target of an intensive optical campaign by the Whole Earth Blazar Telescope (WEBT Villata et al. 2000; Raiteri et al. 2001, see also `http://www.to.astro.it/blazars/webt/`), in which 24 optical telescopes throughout the northern hemisphere participated. Details of the data collection, analysis, cross-calibration of photometry from different observatories, etc. pertaining to the WEBT campaign have been published in Villata et al. (2002). Observations were made in the standard U, B, V, R, and I bands. For the purpose of broadband spectroscopy, the fluxes were corrected for extinction and reddening using a B-band extinction value of $A_B = 1.42$ (Schlegel et al. 1998) and the extinction law of Cardelli et al. (1989). The contribution of the host galaxy was subtracted as described in detail in Villata et al. (2002).

Fig. 1 illustrates that BL Lacertae was in a rather quiescent state during the core campaign, in which the densest light curve sampling was obtained. However, the source underwent a dramatic state transition to an extended high state in mid-September 2000. For this reason, the WEBT campaign was extended until early January of 2001, although with less dense time coverage than during the core campaign.

The WEBT campaign returned optical (R-band) light curves of unprecedented time coverage and resolution. Fig. 2 shows the R-band light curves over the entire core campaign (see also Fig. 2 of Villata et al. 2002). The bottom panel of Fig. 11 (see also Figs. 3 – 5 of Villata et al. 2002) illustrates the microvariability measured for two individual nights during this period. Brightness variations of $\Delta R \sim 0.35$, corresponding to flux variations of $(\Delta F)/F \sim 0.4$, within ~ 1.5 hr have been found. Such rapid microvariability is not exceptional for this source and had been observed before on several occasions (e.g., Miller et al. 1989; Carini et al. 1992; Nesci et al. 1998; Speziali & Natali 1998; Clements & Carini 2001). It is also confirmed by the autocorrelation function of the R-band light curve, which can be well fitted with an exponential with a decay time scale of ~ 2 hr. The observed variability time scale places a constraint on the size of the emitting region of $R \lesssim 1.6 \times 10^{14}\, D$ cm, where $D = (\Gamma[1 - \beta \cos\theta_{\rm obs}])^{-1}$ is the Doppler beaming factor.

2.3. X-ray observations

At X-ray energies, BL Lacertae was observed with the *BeppoSAX* Narrow Field Instruments (NFI) in the energy range 0.1 – 200 keV in two pointings on July 26 – 27 and Oct. 31 – Nov. 2, 2000 (Ravasio et al. 2003). In addition, the source was monitored by the *Rossi X-ray Timing Explorer (RXTE)* Proportional Counter Array (PCA) in 3 short (individual exposures ranging from a few hundred to ~ 2000 s) pointings per week (Marscher et al. 2003, in preparation). Table 1 summarizes the precise times of the two *BeppoSAX* pointings and of the *RXTE PCA* observations closest to the *BeppoSAX* ones, along with the results of the spectral analysis. The details of the *BeppoSAX* observations and the data analysis methods have been published in Ravasio et al. (2003). Note that the PCA had observed BL Lacertae exactly simultaneously with the *BeppoSAX* pointing during the July 26 – 27 observation, while an observation on Nov. 2 started 1 hr after the second *BeppoSAX* pointing.

The drastic change of the activity state of BL Lacertae in mid-September observed in the optical range is accompanied by several large flares in the PCA light curve over a ~ 2 months period (see Fig. 1), but not by a similarly extended high flux state as seen in the optical. In fact, while the average flux level increased only slightly, a higher level of activity was indicated by a higher degree of variability: The average PCA 2 – 10 keV flux

increased from 7.1×10^{-12} ergs cm^{-2} s^{-1} for the period MJD 51725 – 51795 (end of June – early September 2000) to 1.2×10^{-11} ergs cm^{-2} s^{-1} for the period MJD 51800 – 51910 (mid-September – end of December 2000). A constant fit to the quiescent phase resulted in a reduced $\chi^2_\nu = 3.47$, which increased to $\chi^2_\nu = 6.63$ for the remainder of the year. This quantifies the drastically increased 2 – 10 keV X-ray variability on time scales of a few days probed by the PCA monitoring observations, in the active state. However, it also shows that BL Lacertae exhibits significant X-ray variability on this time scale even in the quiescent state.

Fig. 1 also shows that we were extremely lucky to catch BL Lacertae in an exceptional X-ray outburst during our second *BeppoSAX* pointing. In fact, the 2 – 10 keV flux measured on Oct. 31 – Nov. 2, 2000 was the highest ever detected by *Beppo*SAX from this source. Interestingly, the R-band lightcurve indicates a relatively low optical flux, compared to the average flux level after mid-September 2000, coincident with this X-ray outburst. If the optical and soft X-ray fluxes are due to synchrotron emission from the same population of electrons, this could indicate a hardening of the electron spectrum during the flaring state. However, as pointed out and discussed by Ravasio et al. (2003) and in §5, the optical and X-ray spectra during this observation can not be connected by a smooth power-law: the optical fluxes are significantly below a power-law extrapolation of the *Beppo*SAX LECS + MECS spectrum. This could possibly indicate that the optical and X-ray fluxes are coming from separate regions along the jet, possibly also associated with substantial time lags between these emissions.

2.3.1. July 26 – 27

During the July 26 – 27 *BeppoSAX* observation, the source was in a low flux and activity state. This only allowed a rather restricted spectral analysis and the extraction of meaningful light curves with a binning of no less than 1 hr. For details of the spectral and timing analysis, see Ravasio et al. (2003). They tested several spectral models, including a single power-law with free N_H, a single power-law with a fixed value of N_H, and a broken power-law model. In the following, we will concentrate on the results from the analysis with $N_H = 2.5 \times 10^{21}$ cm^{-2}, resulting from the dust-to-gas ratio suggested by Ryter (1996) with $A_B = 1.42$ and the dereddening law as mentioned above in §2.2, and consistent with previous spectral analyses of X-ray observations of BL Lacertae (Sambruna et al. 1999; Madejski et al. 1999; Ravasio et al. 2002). The fit resulted in $\alpha = 0.8 \pm 0.1$. This is perfectly consistent with the result from the contemporaneous *RXTE* PCA observation. The spectral index of $\alpha = 0.8 \pm 0.1$ confirms the low-activity state of the source at that time and indicates that the entire X-ray spectrum

might have been dominated by the low-frequency end of the high-energy component of the broadband SED of BL Lacertae.

The short-term LECS ([0.7 – 2] keV) and MECS ([2 – 10] keV) lightcurves of BL Lacertae during this observation (see Fig. 3 of Ravasio et al. 2003) display a large (factor > 2) flare on a time scale of ~ 4 hr, while the source appears less variable at higher energies. This behavior has been noted in this source before (e.g., Ravasio et al. 2002), and is even more obvious in the Oct 31 – Nov. 2 observation (see next subsection). The low count rate and relatively short exposure time prevents a more detailed analysis of variability features of this observation.

2.3.2. Oct. 31 – Nov. 2

During the second *BeppoSAX* pointing on Oct. 31 – Nov. 2, 2000, we measured the highest 2 – 10 keV flux ever observed with *Beppo*SAX from BL Lacertae. The LECS + MECS spectrum in the 0.3 – 10 keV range was well fitted with a power-law model with fixed $N_H = 2.5 \times 10^{21}$ cm^{-2}, revealing a steep X-ray spectrum with $\alpha = 1.56 \pm 0.03$ (Ravasio et al. 2003). As for the Nov. 26 – 27 observation, the spectral fitting results were consistent with the results from the PCA observations beginning ~ 1 hr after the *Beppo*SAX pointing. In this observation, BL Lacertae was also significantly detected by the PDS up to ~ 50 keV. The PDS spectrum indicates a significant spectral hardening beyond ~ 10 keV with a best-fit spectral index $\alpha_{\rm PDS} = 0.56$ for which, however, no error could be estimated due to the poor photon statistics (Ravasio et al. 2003). The soft shape of the LECS + MECS spectrum clearly indicates that it was dominated by the high-energy end of the low-energy (synchrotron) component in this observation. Evidence for the synchrotron component at soft X-ray energies had been found in BL Lacertae before (Madejski et al. 1999; Ravasio et al. 2002), but this is the first time that this behavior was observed extending all the way out to ~ 10 keV. The spectral hardening evident in the PDS spectrum might indicate the onset of the high-energy component beyond ~ 10 keV.

Fig. 3 displays the LECS and MECS light curves in three different energy channels during the second *BeppoSAX* pointing, along with the two hardness ratios: HR1 = MECS [2 - 4] / LECS [0.5 - 2] and HR2 = MECS [4 - 10] / MECS [2 - 4]. The LECS and MECS light curves show significant variability in all energy channels, with flux variations of factors of $\sim 3 - 4$ on time scales down to $\sim 1 - 2$ hr. The PDS counts were consistent with no variability (constancy probability of ~ 96 %, Ravasio et al. 2003). Ravasio et al. (2003) have calculated the normalized excess variance parameter $\sigma^2_{\rm rms}$ for the three LECS and MECS energy channels and found that $\sigma^2_{\rm rms}$ is slightly decreasing with increasing photon energy.

The LECS and MECS light curves show several individual, well-resolved flares, (e.g., at ~ 29 hr and ~ 49 hr, see Fig. 3). Those flares seem to suggest slightly longer rise than decay time scales, but due to the limited photon statistics, a meaningful, more quantitative assessment of light curve asymmetries is not possible with our present data.

Ravasio et al. (2003) have defined a minimum doubling time scale $T_{\rm short}$ to quantify the energy dependence of the short-term variability time scale, and found no significant trend of this quantity with photon energy. For all three energy LECS + MECS energy channels the minimum doubling time scales were found to be consistent with values of ~ 6 ksec. An estimate of the average rise and decay time scales in the rapid variability can be found through the width of the autocorrelation function (ACF) of the light curves. We have calculated the discrete autocorrelation functions for the three LECS + MECS light curves, and fitted them with an exponential. The results are plotted in Fig. 4 and suggest a decreasing trend of the variability time scale with increasing photon energy, as illustrated in Fig. 5. Clearly, the statistical errors on these measurements are too large to seriously constrain the functional dependence of the ACF widths on photon energy. However, in §6 we suggest a new method to use a decreasing ACF width with increasing photon energy for an independent magnetic-field estimate, and apply this method to the *Beppo*SAX results, tentatively taking the best-fit results at face value.

2.4. Gamma-ray observations

BL Lacertae has been observed by the HEGRA system of imaging Cherenkov telescopes, accumulating a total of 10.5 h of on-source time in Sept. – Nov. 2000. The source was not detected above a 99 % confidence-level upper limit of 25 % of the Crab flux at photon energies above 0.7 TeV (Mang et al. 2001). Assuming an underlying power-law with energy spectral index α, this corresponds to a νF_ν flux limit of $8.65 \times 10^{11} \, \alpha$ Jy Hz at 0.7 TeV.

3. Spectral variability

In this section, we will describe local spectral variability phenomena, i.e. the variability of local spectral (and color) indices and their correlations with monochromatic source fluxes.

3.1. Optical spectral variability

The optical spectral variability of BL Lacertae during our campaign has been investigated in great detail by Villata et al. (2002). In the following, we briefly summarize their results. Villata et al. (2002) have calculated the de-reddened, host-galaxy subtracted B - R color indices for a set of 620 observations taken by the same instrument within 20 minutes of each other, and with individual errors of the B and R magnitudes of no more than 0.04 and 0.03 mag, respectively. Obvious spectral variability was detected, and the color changes were more sensitive to rapid variations than the long-term flux level. During well-sampled, short flares (on time scales of a few hours), the color changes strictly follow the flux variability in the sense that the spectra are harder when the flux is higher (see Fig. 7 of Villata et al. 2002). A plot of B - R vs. R reveals two separate regimes within which the R magnitudes are well correlated with the respective B - R colors. However, there seems to be a discontinuity at $R \sim 14$ mag, separating a high-flux and a low-flux regime. Within each regime, a similar range of B - R colors is observed. Villata et al. (2002) have subsequently fitted the overall long-term flux variability by a cubic spline to the 10-day averages of the R-band light curve and rescaled this spline to pass through the minima of the light curve. Cleaning the B and R fluxes from this base-flux level, they removed the long-term variability from the color-intensity correlation, and found a very clean correlation between the superposed short-term R-band variability and the B - R spectral hardness. This strongly suggests that the optical long-term flux variability (on time scales of weeks) is due to an achromatic mechanism, while the rapid (intraday) variability is clearly chromatic (Villata et al. 2002).

3.2. X-ray spectral variability

Fig. 6 displays the history of the best-fit spectral index from the *RXTE* PCA monitoring observations, along with the PCA light curve. Due to the relatively short exposure times, the errors on the spectral indices are rather large, but a general trend of the local spectral index being softer during strong hard X-ray (2 – 10 keV) flares is discernible. This applies to the overall low state (see, e.g., the flares at MJD 51708 = June 13 or MJD 51770 = Aug. 14) as well as to the high state (e.g., MHD 51826 = Oct. 9 or MJD 51853 = Nov. 5). In order to investigate the question of a hardness-intensity correlation on the timescale of a few days probed by the *RXTE* monitoring, we have constructed a hardness-intensity diagram from the PCA data. To assess the average properties of the source at low fluxes, we have rebinned the points included in Fig.6 in flux bins of $\Delta F_{2-10} = 10^{-12}$ ergs cm^{-2} s^{-1} for all individual points with 2 – 10 keV flux of less than 1.8×10^{-11} ergs cm^{-2} s^{-1}, calculating average fluxes and spectral indices weighted by the inverse of the errors of the spectral-index measurements.

Data points with larger 2 – 10 keV fluxes are plotted individually. The result is shown in Fig. 7. The figure illustrates that high PCA 2 – 10 keV fluxes above $\sim 2 \times 10^{-11}$ ergs cm^{-2} s^{-1} are always characterized by soft spectra with $\alpha \geq 1$, indicating decaying νF_ν spectra. This confirms the notion mentioned earlier that large-amplitude X-ray flares might be dominated by the variability of the low-energy (synchrotron) component, extending into the PCA energy range during flaring activity. No significant trend of the local spectral index with X-ray flux is discernible at low X-ray flux states.

The X-ray spectral variability on short (intra-day) time scales can be characterized through variations of the *BeppoSAX* hardness ratios HR1 and HR2 as defined in §2.3.2. Their history during the second *BeppoSAX* observation on Oct. 31 – Nov. 2 is plotted along with the LECS and MECS light curves in Fig. 3. Considering the entire Oct. 31 – Nov. 2 observation, we only find a very weak hint of an anti-correlation of HR1 with the soft LECS (0.5 – 2) keV flux and a positive correlation of HR2 with the medium-energy MECS (4 – 10) keV flux. These trends become slightly more apparent when following individual, well-resolved flares. Figs. 8 and 9 show two examples of such hardness-intensity diagrams for the flares around 45 hr and 48 hr of Oct. 31 (see Fig. 3). A weak hardness-intensity anti-correlation at soft X-rays (HR1 vs. LECS) and a positive hardness-intensity correlation at medium-energy X-rays (HR2 vs. MECS) can be seen. The flare around 48 hr also shows weak evidence for spectral hysteresis as found previously in several HBLs such as Mrk 421 and PKS 2155-304 (e.g., Takahashi et al. 1996; Kataoka et al. 2000). Such spectral hysteresis phenomena have been modelled in detail with pure SSC models for the case of HBLs (e.g., Kirk et al. 1998; Georganopoulos & Marscher 1998; Kataoka et al. 2000; Kusunose et al. 2000; Li & Kusunose 2000) and recently also predicted for intermediate and low-frequency peaked BL Lacs by Böttcher & Chiang (2002).

4. Inter-band cross-correlations and time lags

In this section, we investigate cross-correlations between the measured light curves at different frequencies, within individual frequency bands as well as broadband correlations between different frequency bands.

4.1. Radio correlations

We have calculated the discrete correlation functions (DCFs; Edelson & Krolik (1988)) between the light curves at different radio frequencies for a variety of sampling time steps

$\Delta\tau$. We did not find any conclusive hints of correlations of the 37 GHz light curve with other radio light curves or light curves at other wavelength bands. This might be the result of the poor sampling of the 37 GHz light curve. Fig. 10 displays the DCFs of the various radio light curves at $\nu < 22$ GHz with the 14.5 GHz light curve as reference for a sampling time scale of $\Delta\tau = 5$ d. We chose the 14.5 GHz reference light curve because it is the best sampled radio light curve in our data set. The DCFs show evidence for a correlation between the variability at the various radio frequencies. We have subsequently fitted the DCFs with Gaussians to determine the most likely time delays between the signals at different radio frequencies. We have repeated this procedure for several other sampling time scales (specifically, $\Delta\tau = 3$ d and $\Delta\tau = 7$ d) and found that only the result pertaining to the 14.5 GHz vs. 22 GHz DCF remained robust, indicating a time lag between the 14.5 GHz and the 22 GHz light curve, with the 14.5 GHz light curve lagging behind the 22 GHz one by ~ 15 d. The best fit is indicated by the solid curve in the top panel of the figure.

In order to test the statistical significance of the high-frequency radio time lag, we have performed a series of 10,000 Monte-Carlo simulations, assuming uncorrelated variability patterns between the 14.5 GHz and the 22 GHz light curves. Specifically, we have simulated random light curves for the 22 GHz fluxes and performed the same DCF and Gaussian fitting analysis as we had done with the actual data. The simulated 22 GHz light curves were constrained by the measured maximum and minimum fluxes in our data set and by a short-term doubling time scale of 40 d for rapid fluctuations on $\Delta t \leq 10$ d, and a long-term doubling time scale of 4 mo. Simulated data points were constructed for the times of the actual 22 GHz measurements in our data set. We find a probability of 12.3 % that these simulated random light curves show a DCF amplitude higher than resulting from the real 22 GHz flux history, with an acceptable Gaussian fit to the DCF. Thus, the measured time delay can not be considered statistically significant. This might be, at least in part, due to the fact that the data train from our campaign is relatively short.

4.2. Radio – optical correlations

We also calculated the DCFs between the light curves at the various radio and the optical (R-band) light curves, and calculated the best-fit time delay, as described in the previous paragraph. This resulted in low-significance detections of time delays of ~ 45 – 50 d of the 8, 14.5, and 37 GHz radio light curves behind the optical ones. However, these results have to be considered with great caution since our data set only spans about half a year. On the basis of historical data, characteristic time delays of ~ 1 – 4.5 years between the radio and optical variability had been found previously (Bregman et al. 1990). Thus,

our correlations may well be a chance coincidence in the sense that the observed radio and optical variability patterns may not correspond to the same epoch of activity of the central source. A more comprehensive study of the long-term behaviour of BL Lacertae, including the results of this multiwavelength campaign will be the subject of subsequent work (e.g., Villata et al. (2003)).

As reported by Villata et al. (2002), the light curves in the different optical bands (U, B, V, R, I) are well correlated (with the hardness - brightness correlation described in §3.1), but no significant, measurable time delays between the B and the R band (the best sampled optical light curves in our campaign) were found.

4.3. X-ray – optical correlations

The extraordinary time coverage of the R band light curves during the core campaign allows us to do a meaningful comparison of the intraday variability patterns at optical and X-ray frequencies during our first *Beppo*SAX observation of July 26/27. Fig. 11 displays the LECS [0.7 – 2] keV and the contemporaneous R-band light curve during this observation. From visual inspection, it seems that the R-band light curve closely tracks the LECS light curve with a delay of $\sim 4 - 5$ hr (indicated by the dotted arrows in Fig. 11). However, the DCF between the R-band flux and the LECS count rate (see Fig. 12) instead identifies a stronger apparent signal from an anti-correlation with an optical – X-ray delay of ~ 3 hr. The dominant features probably identified by the DCF analysis are indicated by the dot-dashed arrows in Fig. 11. Note that the DCF is defined so that negative τ corresponds to a lead of the X-rays. Unfortunately, the limited statistics of the *Beppo*SAX light curve prevents a more in-depth analysis of the possible optical – X-ray correlation on these short time scales. Any claimed correlation does not hold up to a statistical significance test. However, if we assume that the optical lag of $\sim 4 - 5$ hr is real and can be interpreted as due to synchrotron cooling, it allows an independent magnetic field estimate, which will be quantified in §6. Interestingly, the resulting magnetic field is in good agreement with an independent estimate from a basic equipartition argument.

The DCF also identifies a strong, apparent correlation between optical and X-ray fluxes with an R-band lead of ~ 9 hr, which seems to arise from the large optical flare at ~ 8 hr, preceding the LECS flare at ~ 17 hr (see long-dashed arrows in Fig. 11). However, we believe that this might be an artifact due to the limited duration and time resolution of the LECS light curve. Note that this 9 hr time scale spans over about half the duration of the entire *BeppoSAX* LECS light curve for this observation. We have also looked for correlations between the R band and X-ray fluxes on longer time scales, applying the DCF analysis to

the *RXTE* PCA, ASM (daily averages), and R-band light curves. No significant time delays were detected.

We have also investigated possible time delays between the different *Beppo*SAX LECS and MECS light curves displayed in Fig. 3 for the Oct. 31 – Nov. 2 observation. While the DCFs show evidence for a positive correlation between all of these light curves, no measurable time delays could be identified.

5. Broad-band spectral energy distributions

We have constructed simultaneous broadband spectral energy distributions (SEDs) for the times of the two *Beppo*SAX pointings. They are shown in Fig. 13. For the radio fluxes, we selected the measurements closest in time to the center of the respective *Beppo*SAX exposure. We generally had multiple optical flux measurements throughout the times of the *Beppo*SAX exposures. To construct the SEDs, we have calculated the average optical flux in each band from the de-reddened, host-galaxy-subtracted individual flux measurements (see §2.2) over the *Beppo*SAX exposure time, and indicate the (in some cases rather substantial) range of variability over that period by the error bars on the optical fluxes.

We represent the best-fit power-law spectra of the *Beppo*SAX LECS + MECS measurements as well as the simultaneous or quasi-simultaneous *RXTE* PCA measurements as bow-tie outlines in the SEDs. For orientation purposes only, we also indicate the EGRET flux from the major γ-ray outburst of BL Lacertae in July 1997 (Bloom et al. 1997). Included are also the anticipated sensitivity limits of current and future atmospheric Čerenkov telescope facilities, and the HEGRA upper limit from the observations in Sept. – Nov., 2000.

Fig. 13 illustrates the drastically different activity states between the July 26/27 and the Oct. 31 – Nov. 2 *Beppo*SAX observations. In the July 26/27 SED, the synchrotron peak appears to be located at frequencies clearly below the optical range (probably at $\nu_{\rm sy} \sim 10^{14}$ Hz), and the synchrotron emission cuts off at a frequency near or below $\sim 10^{17}$ Hz. In contrast, the SED of Oct. 31 – Nov. 2 shows clear evidence for the presence of the synchrotron component out to at least 10 keV, and the synchrotron peak might be located in the optical range at a few times 10^{14} Hz. For illustration purposes, we have also plotted the *RXTE* PCA spectrum of the observation a few hours before the beginning of the Oct. 31 – Nov. 2 *Beppo*SAX pointing. This PCA spectrum shows characteristics rather similar to the low-state spectrum, and illustrates the drastic nature of the short-term X-ray variability. This might indicate that the rapid variability of BL Lacertae is probably driven by short episodes of injection / acceleration of high-energy electrons into the emitting volume.

Ravasio et al. (2003) have shown that the extrapolation of the optical spectrum towards higher frequencies does not connect smoothly with the contemporaneous soft X-ray spectrum (see their Fig. 5). They have considered various possible explanations of this discrepancy: (a) a variable dust-to-gas ratio, which could cause a larger degree of reddening during the Oct. 31 – Nov. 2 observations, (b) the Bulk-Compton process (Sikora et al. 1997), which could provide an additional emission component at soft X-rays due to Compton upscattering of external photons by a thermal component of electrons in the emitting volume, (c) a second component of relativistic electrons, providing an additional source of synchrotron emission at soft X-rays, and (d) the flattening effect of the Klein-Nishina cutoff on the cooling electron distribution, leading to a high-energy bump in the synchrotron emission (see Dermer & Atoyan 2002, for a recent application of this idea to the optical – X-ray spectra of individual knots in jets of radio galaxies detected by *Chandra*). While the first two of the ideas listed above were found to lead to rather unrealistic inferences about the environment of the AGN and the underlying accretion-disk spectrum, respectively, the latter two scenarios will be considered further in our modelling efforts in our companion theory paper (Böttcher & Reimer 2003, in preparation). However, it seems also possible that this misalignment could be an artifact of the flux averaging over the ~ 1.5 days of the *Beppo*SAX observations, including multiple short-term flares of only a few hours each. In order to test for this possibility, it will be essential to use a fully time-dependent AGN emission model and do the flux averaging in a similar way as was done with the data to construct the SEDs displayed in Fig. 13.

6. Generic parameter estimates

In this section, we discuss some general constraints on source parameters that will be relevant for detailed spectral and variability modelling of BL Lacertae. We will first (§6.1) focus on three independent methods to estimate the magnetic field, and then turn to other properties, such as the co-moving Lorentz factors of electrons in the jet, the bulk Lorentz and Doppler boosting factors, the kinetic luminosity of the jet, and the source size.

6.1. The magnetic field

In §2.3, we had investigated the energy-dependent width of the autocorrelation functions of the X-ray variability during the Oct. 31 – Nov. 2 *Beppo*SAX observation (see Fig. 5). Assuming that the rise time of short-term flaring is not significantly dependent on energy (i.e., it is dominated by light-crossing time constraints rather than an energy-dependent

acceleration time scale), the width of the ACF should yield an estimate of the cooling time scale $\tau_c(E)$ of the electrons responsible for the emission at energy E as a function of photon energy. Specifically, in that case, we expect that $\tau_{\rm ACF}(E) = \tau_0 + \tau_{\rm cool}(E)$. If the LECS + MECS spectrum is indeed dominated by synchrotron emission, we can associate an observed photon energy $E = 1\,E_{\rm keV}$ keV with the characteristic photon energy of synchrotron emitting electrons, $E_{\rm keV} = 1.4{\times}10^{-11}\,D\,B_{\rm G}\,\gamma^2$, where $B = 1\,B_{\rm G}$ G is the co-moving magnetic field, and γ is the electron Lorentz factor. If the electron cooling is dominated by synchrotron and/or external Compton cooling in the Thomson regime, we have $\dot\gamma = -(4/3)\,c\,\sigma_T\,(u_B/m_e c^2)\,(1 + k)\,\gamma^2$, where u_B is the energy density in the magnetic field, and $k \equiv u_{\rm ext}/u_B$ is the ratio of the energy density in an external photon field to the magnetic-field energy density (all quantities in the co-moving frame of the emitting region). This yields the synchrotron + EC cooling time (in the observer's frame) of

$$\tau_{\rm cool,sy}(E) = 2.9 \times 10^3\,D^{-1/2} B_{\rm G}^{-3/2}\,(1 + k)^{-1}\,E_{\rm keV}^{-1/2}\ {\rm s.} \tag{1}$$

Fitting a function $\tau_{\rm ACF}(E) = \tau_0 + \tau_1\,E_{\rm keV}^{-1/2}$ to the energy dependence shown in Fig. 5 (solid line) yields a best-fit value of $\tau_1 = (7800{\pm}1400)$ s, which implies $B = (0.24{\pm}0.03)\,D_1^{-1/3}\,(1+k)^{-2/3}$ G, where $D_1 = D/10$.

Alternatively, if electron cooling is dominated by the synchrotron-self-Compton process, the relevant photon field energy density is $u_{\rm sy}$, which we can approximate as

$$u_{\rm sy} \approx \tau_{\rm T}\,u_B\,\frac{q-1}{3-q}\,\gamma_1^{q-1}\,\gamma_2^{3-q}, \tag{2}$$

where $\tau_{\rm T} = n_e\,\sigma_T\,R_{\rm B}$ is the radial Thomson depth of the emitting region, and q is the spectral index of the *injected* electron spectrum, $Q(\gamma) = Q_0\,\gamma^{-q}$ for $\gamma_1 \le \gamma \le \gamma_2$. The decay time scale of the light curve at a characteristic synchrotron photon energy E will then correspond to the Compton cooling time scale of electrons at the high-energy end of the electron spectrum, γ_2, at the time when their characteristic synchrotron frequency equals E. Thus, the relevant cooling rate is

$$\frac{d\gamma_2}{dt} = -\frac{4}{3}c\,\sigma_T\,\frac{U_B}{m_e c^2}\,\frac{q-1}{3-q}\,\tau_{\rm T}\,\gamma_1^{q-1}\,\gamma_2^{5-q}. \tag{3}$$

This yields a characteristic cooling time (in the observer's frame) of

$$\tau_{\rm cool,SSC} = 7.7 \times 10^8\,\frac{3-q}{q-1}\,(2.4 \times 10^5)^{q-4}\,\tau_{\rm T}^{-1}\,\gamma_1^{1-q}\,B_{\rm G}^{-q/2}\,D^{(2-q)/2}\,E_{\rm keV}^{(q-4)/2}\ {\rm s.} \tag{4}$$

Leaving the index q free, we find a best-fit energy dependence of $\tau_{\rm cool} = \tau_0 + \tau_1 \, E_{\rm keV}^{-\zeta}$ with $\zeta = 0.50 \pm 0.14$, which yields the same energy dependence as in the synchrotron-cooling case. However, the optical spectral index of $\alpha_o \sim 1.2$ corresponds to a time average (or equilibrium in the case of a balance between particle injection and radiative cooling) electron spectral index of $p = 3.4$, indicating a value of $q = 2.4$. Fixing $q = 2.4$ (i.e., $\zeta = 0.8$), the fit is still perfectly consistent with the measured energy dependence, as indicated by the dashed line in Fig. 5. From the best-fit value of $\tau_1 = (7020 \pm 1980)$ s, we can derive a magnetic-field estimate of $B = (0.20 \pm 0.05) \, \tau_{\rm T,-6}^{-5/6} \, (\gamma_1/100)^{-7/6} \, D_1^{-1/12}$ G. With the available data, the two cooling scenarios can obviously not be distinguished, and the estimates may be rather uncertain due to the possible effect of energy-dependent acceleration times and energy dependent photon propagation times through the blob. Thus, our magnetic field estimates based on Eqs. 1 and 4 are meant more as a suggestion for the analysis of higher-quality data from future observations by X-ray observatories with higher throughput, like *Chandra* or *XMM-Newton* or the planned Constellation-X mission, rather than a realistic magnetic field estimate from our currently available *BeppoSAX* data.

Another independent magnetic-field estimate could be obtained from the time delay between the *Beppo*SAX LECS [0.7 – 2] keV and the R-band light curves of $\Delta t^{\rm obs} \sim 4 - 5$ hr, for which Fig. 11 shows tantalizing, though not statistically significant, support. Assuming that the correlation is real and the delay is caused by synchrotron cooling of high-energy electrons with characteristic observed synchrotron photon energy $E_{\rm sy,0} = E_0$ keV to lower energies with corresponding synchrotron energy $E_{\rm sy,1} = E_1$ keV, we find a magnetic-field estimate analogous to Eq. 1:

$$B_{\rm delay} = 0.4 \, D_1^{-1/3} \, (1 + k)^{-2/3} \, (\Delta t_h^{\rm obs})^{-2/3} \, (E_1^{-1/2} - E_0^{-1/2})^{2/3} \text{ G.} \tag{5}$$

where $\Delta t_h^{\rm obs}$ is the observed time delay in hours. Using $\Delta t_h^{\rm obs} = 5$, $E_0 = 1$ for the LECS, and $E_1 = 5.6 \times 10^{-4}$ for the R band, we find

$$B_{\rm delay,RX} = 1.6 \, D_1^{-1/3} \, (1 + k)^{-2/3} \text{ G.} \tag{6}$$

We need to point out that Eq. 6 may, in fact, slightly overestimate the actual magnetic field since at least the optical synchrotron emitting electrons may also be affected by adiabatic losses and escape. Depending on the details (geometry and mechanism) of the jet collimation, those processes can act on time scales as short as the dynamical time scale, which is constrained by the observed minimum variability time scale of $\Delta t_{\rm dyn} \lesssim 1.5$ hr (in the observer's frame). Another note of caution that needs to be kept in mind is that the rather large sampling time scale of the X-ray light curve of $\Delta t = 1$ hr, precludes the estimation of magnetic fields larger than $B_{\rm delay,max} \sim 4.8 \, D_1^{-1/3} \, (1 + k)^{-2/3}$ G from delays between the

optical and X-ray light curves. Consequently, magnetic fields larger than $B_{\rm delay,max}$ can not be excluded on the basis of the present analysis.

In principle, one could also derive an analogous estimate for the SSC-cooling case. However, it is unlikely that SSC cooling can dominate when the bulk of the synchrotron emission has evolved down to optical frequencies. Thus, it would not be realistic to apply such an estimate to the optical – X-ray time delay.

A third independent estimate of the co-moving magnetic field can be found by assuming that the dominant portion of the time-averaged synchrotron spectrum is emitted by a quasi-equilibrium power-law spectrum of electrons with $N_e(\gamma) = n_0 \, V_B \, \gamma^{-p}$ for $\gamma_1 \le \gamma \le \gamma_2$; here, V_B is the co-moving blob volume. The normalization constant n_0 is related to the magnetic field through an equipartition parameter $e_B \equiv u_B / u_e$ (in the co-moving frame). Note that this equipartition parameter only refers to the energy density of the electrons, not accounting for a (possibly greatly dominant) energy content of a hadronic matter component in the jet. Under these assumptions, the νF_ν peak synchrotron flux $f_\epsilon^{\rm sy}$ at the dimensionless synchrotron peak energy $\epsilon_{\rm sy}$ is approximately given by

$$f_\epsilon^{\rm sy} = (D \, B)^{7/2} \, \frac{\pi \, c \, \sigma_{\rm T}}{288 \, d_L^2} \, \left([1 + z] \, \epsilon_{\rm sy} \, B_{\rm cr} \right)^{1/2} \, \frac{p - 2}{e_B \, m_e c^2} \tag{7}$$

where $B_{\rm cr} = 4.414 \times 10^{13}$ G. Note that the electron spectrum normalization used to derive Eq. 7 is based on the synchrotron spectrum above the synchrotron peak, where the underlying electron spectrum always has an index of $p \ge 3$. Eq. 7 yields a magnetic-field estimate of

$$B_{e_B} = 9 \, D_1^{-1} \left(\frac{d_{27}^4 \, f_{-10}^2 \, e_B^2}{[1 + z]^4 \, \epsilon_{\rm sy,-6} \, R_{15}^6 \, [p - 2]} \right)^{1/7} \; {\rm G}, \tag{8}$$

where $f_{-10} = f_\epsilon^{\rm sy} / (10^{-10}$ ergs cm^{-2} s$^{-1})$, $\epsilon_{\rm sy,-6} = \epsilon_{\rm sy} / 10^{-6}$, and $R_{15} = R_B / (10^{15}$ cm$)$. With $d_{27} = 0.87$, $f_{-10} = 1$, $\epsilon_{\rm sy,-6} = 4$, $R_{15} = 2$, and $p = 3.4$, this yields

$$B_{e_B} = 3.6 \, D_1^{-1} \, e_B^{2/7} \; {\rm G}. \tag{9}$$

This is in excellent agreement with the estimate from the X-ray – optical delay, if the Doppler factor is slightly larger than 10 and/or the magnetic-field equipartition parameter is slightly less than 1. We thus conclude that a magnetic field of $B \sim 2 \, e_B^{2/7}$ G might be a realistic value for BL Lacertae. We point out that the estimates in Eq. 5 and 8 should be valid for any model which represents the low-energy component of the blazar SED as synchrotron emission from relativistic electrons, which is the case for virtually all variations of leptonic and hadronic jet models.

6.2. Other relevant parameters

Based on the magnetic-field estimate of 1.5 – 2 G, the approximate location of the synchrotron peak of the SEDs of BL Lacertae at $\nu_{\rm sy} \sim 10^{14}$ Hz allows us to estimate that the electron energy distribution in the synchrotron emitting region should have a peak at $\langle\gamma\rangle \sim 1.4 \times 10^3 \, D_1^{-1/2}$. The location of the synchrotron cutoff in the quiescent state at $\nu_{\rm sy,co}^{\rm qu} \lesssim 10^{17}$ Hz then yields a maximum electron energy in the quiescent state of $\gamma_2^{\rm qu} \lesssim 4 \times 10^4 \, D_1^{-1/2}$, while the synchrotron cutoff in the flaring state at $\nu_{\rm sy,co}^{\rm fl} \sim 2.4 \times 10^{18}$ Hz yields $\gamma_2^{\rm fl} \sim 2 \times 10^5 \, D_1^{-1/2}$.

The superluminal-motion measurements mentioned in the introduction place a lower limit on the bulk Lorentz factor $\Gamma \gtrsim 8$, and we expect that the Doppler boosting factor D is of the same order. Since, unfortunately, we only have upper limits on the VHE γ-ray flux during our campaign, and no measurements in the MeV — GeV regime, no independent estimate from $\gamma\gamma$ opacity constraints can be derived. However, such an estimate was possible for the July 1997 γ-ray outburst and yielded $D \gtrsim 1.4$ (Böttcher & Bloom 2000), which is a much weaker constraint than derived from the superluminal motion observations. From the optical and X-ray variability time scale, we find an upper limit on the source size of $R_B \lesssim 1.6 \times 10^{15} \, D_1$ cm.

If the electrons in the jet are efficiently emitting most of their co-moving kinetic energy before escaping the emission region (fast cooling regime), then the kinetic luminosity of the leptonic component of the jet would have to be $L_j^e \gtrsim 4\pi \, d_L^2 \, (\nu F_\nu)^{\rm pk} / D^4 \sim 10^{41} \, D_1^{-4}$ ergs s^{-1}. If the electrons are in the slow-cooling regime (i.e. they maintain a substantial fraction of their energy before escaping the emitting region) and/or the jet has a substantial baryon load (for a recent discussion see, e.g., Sikora & Madejski 2000), the kinetic energy of the jet would have to be accordingly larger.

In both leptonic and hadronic blazar models, one needs an estimate of the energy density in the external photon field. In the case of leptonic models, this determines the external-Compton processes, in hadronic models, pγ processes on external photons depend on this quantity. For this purpose, an estimate of the average distance of the BLR from the central engine is needed, which can be achieved in the following way. The most recent determination of the mass of the central black hole in BL Lacertae can be found in Wu & Urry (2002). They find a value of $M_{\rm BH} = 1.7 \times 10^8 \, M_\odot$. Then, if the width of the emission lines measured by Vermeulen et al. (1995), Corbett et al. (1996), and Corbett et al. (2000) is interpreted as due to Keplerian motion of the BLR material around the central black hole, we find an estimate of the average distance of the line producing material of $\bar{r}_{\rm BLR} \sim 4.7 \times 10^{-2}$ pc.

All of these estimates are model independent and provide a generic framework for all rel-

ativistic jet models (in particular, leptonic as well as hadronic models) aimed at reproducing the broadband SEDs and variability of BL Lacertae during our campaign.

7. Summary

We have presented the observational results of an extensive multiwavelength monitoring campaign on BL Lacertae in the second half of 2000. The campaign consisted of simultaneous or quasi-simultaneous observations at radio, optical, and X-rays frequencies. Also, a simultaneous upper limit at > 0.7 TeV was obtained with the HEGRA atmospheric Čerenkov telescope facility. We have presented light curves, spectral variability characteristics, and broadband SEDs of BL Lacertae during our observations. We have also looked for cross-correlations and time lags between different frequency bands as well as between narrow energy bands within the same frequency bands.

The WEBT optical campaign achieved an unprecedented time coverage, virtually continuous over several 10 – 20 hour segments. It revealed intraday variability on time scales of ~ 1.5 hours and evidence for spectral hardening associated with increasing optical flux. The multiwavelength campaign included two $\sim 25 - 30$ ksec pointings with the *Beppo*SAX satellite.

During the campaign, BL Lacertae underwent a major transition from a rather quiescent state prior to September 2000, to a long-lasting flaring state throughout the rest of the year. This was also evident in the X-ray activity of the source. The *Beppo*SAX observations on July 26/27 revealed a rather low X-ray flux and a hard spectrum, while a BeppoSAX pointing on Oct. 31 – Nov. 2, 2000, indicated significant variability on time scales of $\lesssim$ a few hours, and provided evidence for the synchrotron spectrum extending out to ~ 10 keV during that time.

Details of the data analyses as well as results pertaining specifically to the optical and X-ray observations have been published in two previous papers on this campaign (Villata et al. 2002; Ravasio et al. 2003). The new results presented in this paper for the first time include:

- We found a weak, low-significance indication of a delay of the 14.5 GHz light curve behind the 22 GHz light curve of ~ 15 d. No significant delays between the 14.5 GHz light curve and the lower-frequency light curves on the time scales covered by our campaign ($\lesssim 1/2$ yr) were detected.

- We found that the optical intraday variability during the first BeppoSAX observation

on July 26/27 seems to trace the soft X-ray variability with a time delay of $\sim 4 - 5$ hr. If this delay is real and the result of synchrotron cooling of ultrarelativistic electrons, we can derive a magnetic field estimate of $B_{\rm delay,RX} = 1.6\, D_1^{-1/3}\, (1 + k)^{-2/3}$ G.

- An additional, model-independent estimate of the magnetic field in the BL Lacertae jet system from equipartition arguments yielded $B_{e_B} = 3.6\, D_1^{-1}\, e_B^{2/7}$ G.

- We suggest a new method to estimate the magnetic field from the width of the autocorrelation function of light curves at different photon energies, assuming that differences in the ACF widths are a measure of the energy-dependent radiative cooling time scale. In the case of the data available from our campaign, this energy dependence is poorly constrained. However, taking the best-fit parameters at face value, we demonstrate our new method and find magnetic field estimates which are somewhat lower than inferred from the optical – X-ray delay and from the equipartition argument.

- We investigated the correlation between X-ray spectral hardness and intensity. The *RXTE* PCA data show a general trend of spectral softening during the highest flux states on the time scale of several days sampled by those observations. For the second *Beppo*SAX observation, we could isolate individual short-term flares of a few hours, and plot hardness-intensity diagrams over those individual flares. At soft X-rays, we confirm the general trend of spectral softening during flares, while the medium-energy X-rays show the opposite trend. In addition, some (though not all) short-term flares show weak evidence for X-ray spectral hysteresis.

Our campaign has revealed an extremely rich phenomenology of X-ray spectral variability features which provide great potential for a deeper understanding of the nature and energetics of the jets of low-frequency peaked and intermediate BL Lac objects. However, the detection of these spectral variability phenomena were at (or even beyond) the limits of the capabilities of the *Beppo*SAX instruments. We strongly encourage future observations with the new generation of X-ray telescopes, in particular *Chandra* and *XMM-Newton*, to provide a more reliable and detailed study of these X-ray spectral variability phenomena.

Detailed modeling of the SEDs and variability properties of BL Lacertae measured during this campaign will be presented in a companion paper (Böttcher & Reimer 2003, in preparation).

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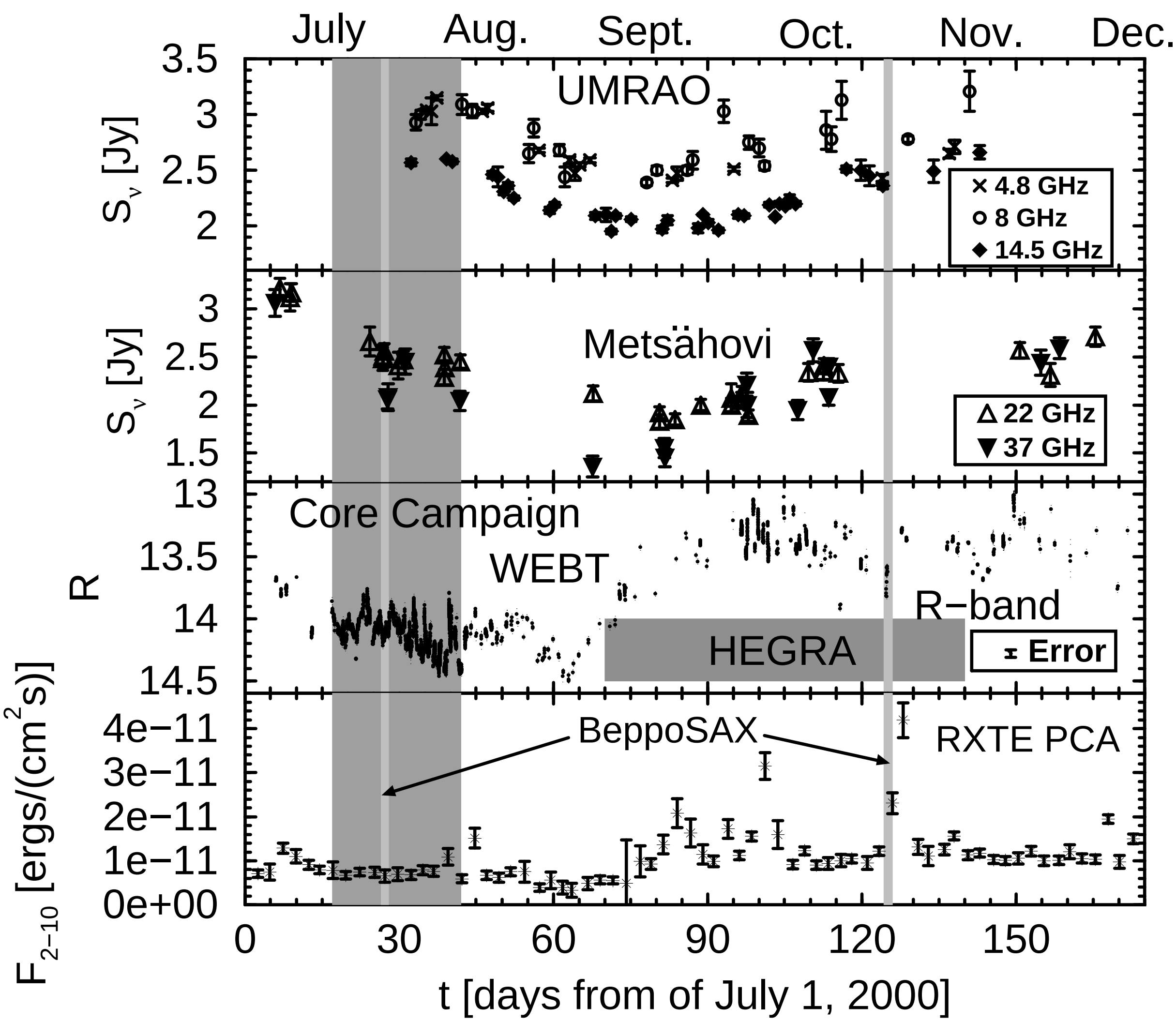

Fig. 1.— Time line of the broadband campaign on BL Lacertae in 2000. The dark-shaded areas indicate the duration of the core campaign, July 17 – August 11, 2000 and of the HEGRA observations (collecting a total of 10.5 hours of on-source time); the light-shaded areas indicate the times of our two BeppoSAX pointings. For clarity, the error bars on the R-band magnitudes have not been plotted individiually. The inset in the lower-right corner of the third panel shows the typical error bar for measurements outside the core campaign; the errors are typically a factor of 3 smaller than this during the core campaign.

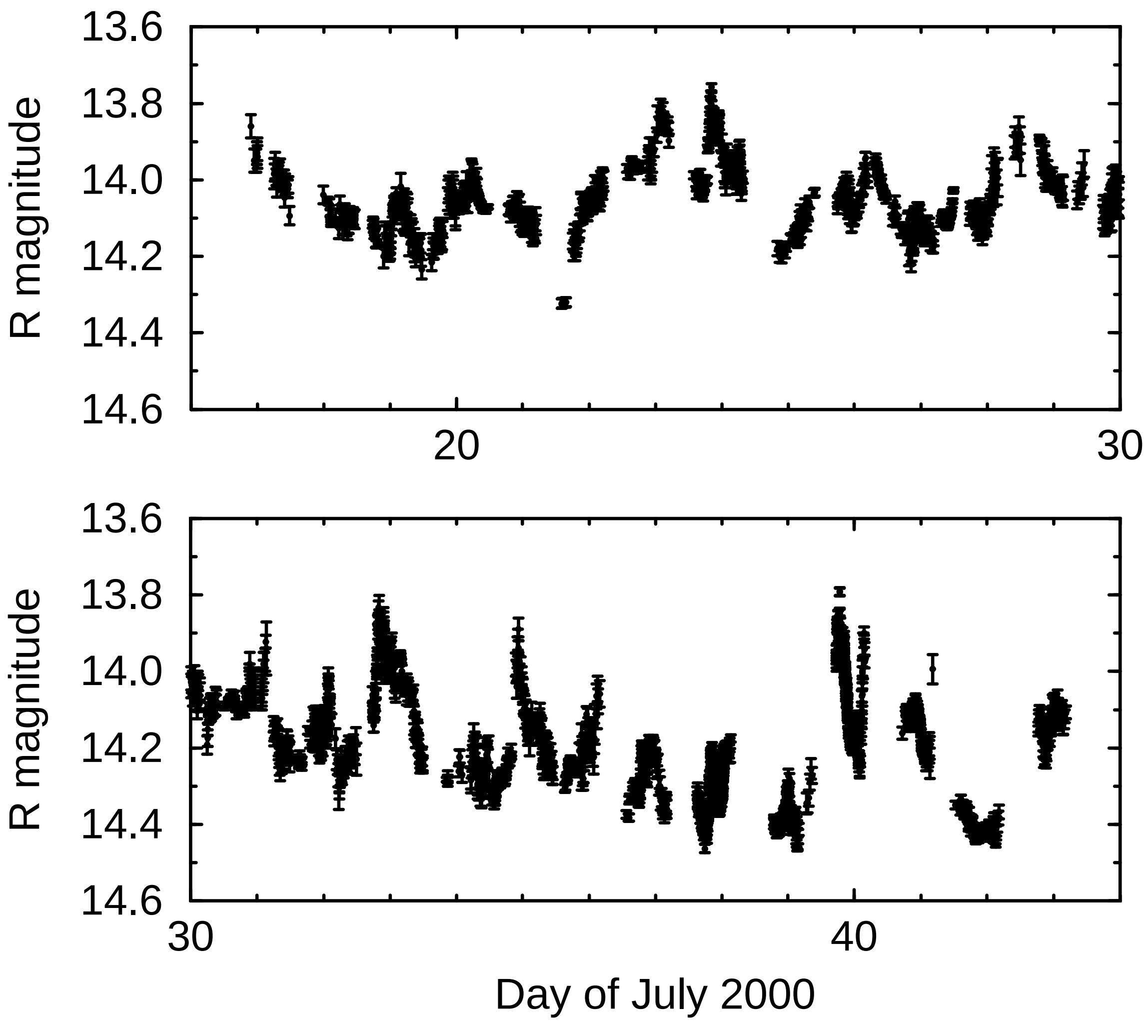

Fig. 2.— Optical (R-band) light curve of BL Lacertae during the core campaign of July 17 – August 11, 2000 (Villata et al. 2002).

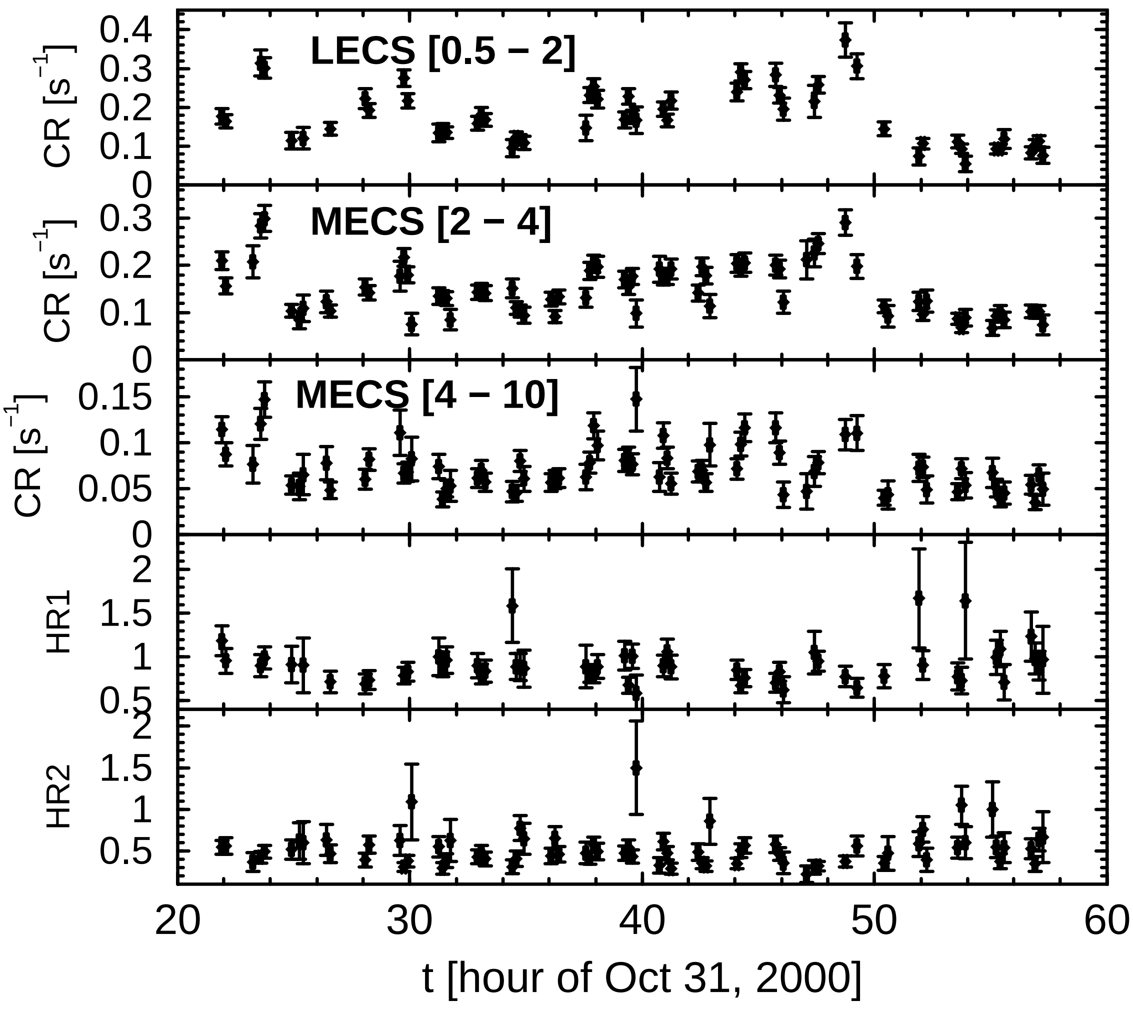

Fig. 3.— Light curves in three different energy channels of the *BeppoSAX* LECS + MECS observations on Oct. 31 – Nov. 2, 2000. The two lower panels show the hardness ratios HR1 = MECS [2 - 4] / LECS [0.5 - 2] and HR2 = MECS [4 - 10] / MECS [2 - 4].

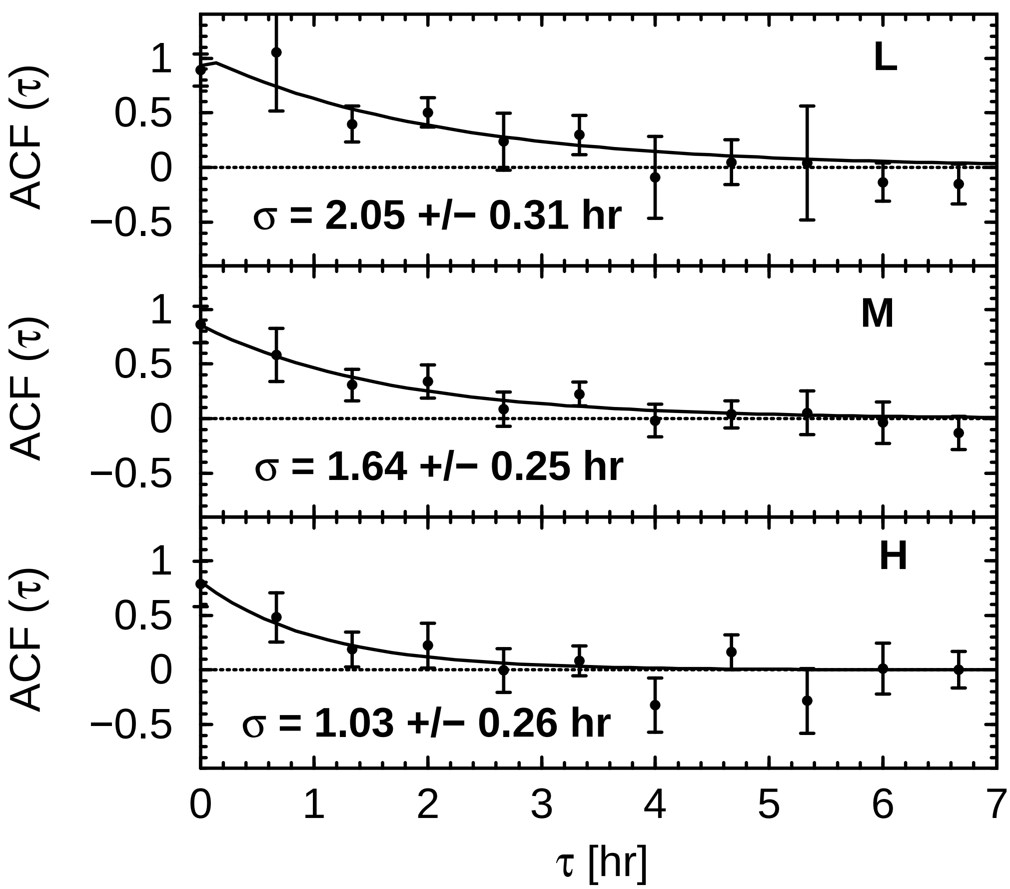

Fig. 4.— Discrete autocorrelation functions (ACFs) of the X-ray flux in three energy channels: L = LECS (0.5 - 2) keV, M = MECS (2 - 4) keV, H = MECS (4 - 10) keV. The ACFs have been fitted with a symmetric constant + exponential. σ as quoted in the individual panels is the best-fit value of the decay time constant.

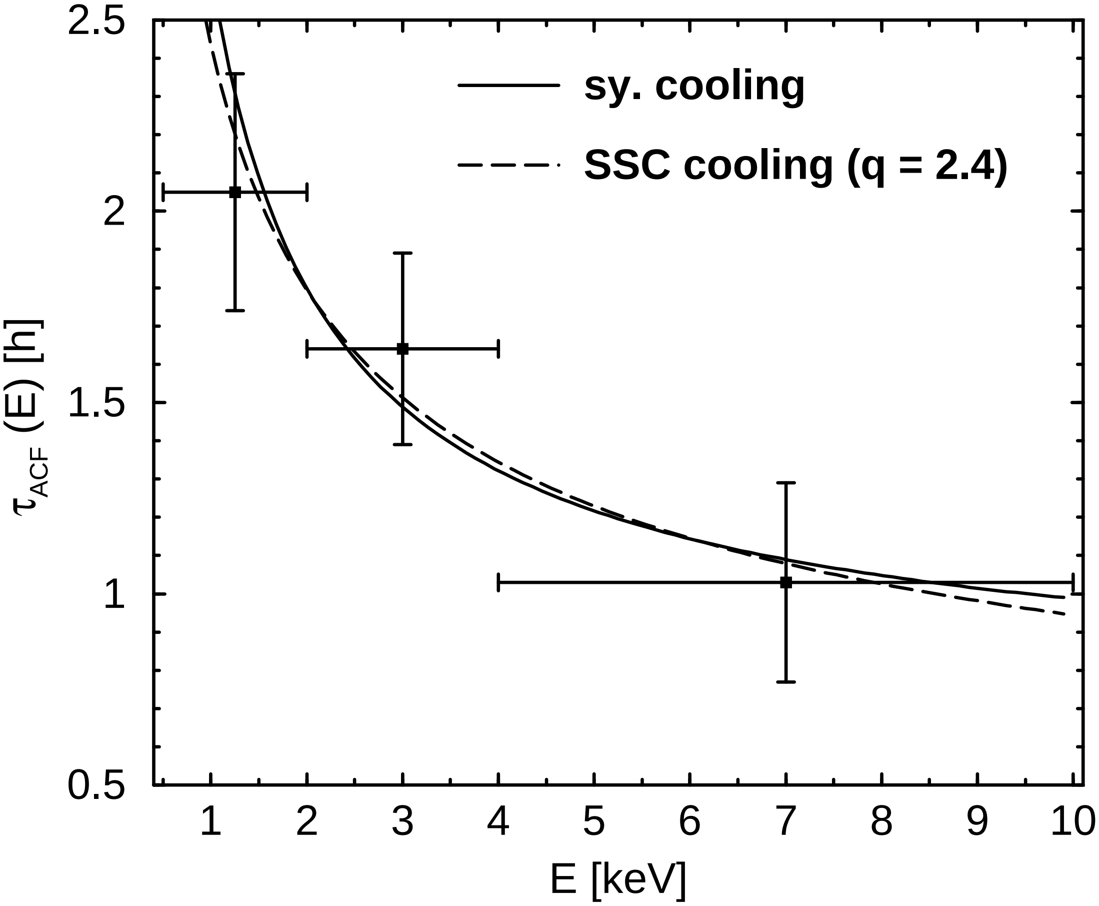

Fig. 5.— The widths of the discrete autocorrelation functions (ACFs) of the light curves in the LECS + MECS energy range, as a function of synchrotron photon energy. The solid curve is the best fit of this energy dependence assuming it is caused by synchrotron + external-Compton cooling; the solid curve is a fit assuming dominant SSC cooling with an injection electron spectral index of $q = 2.4$.

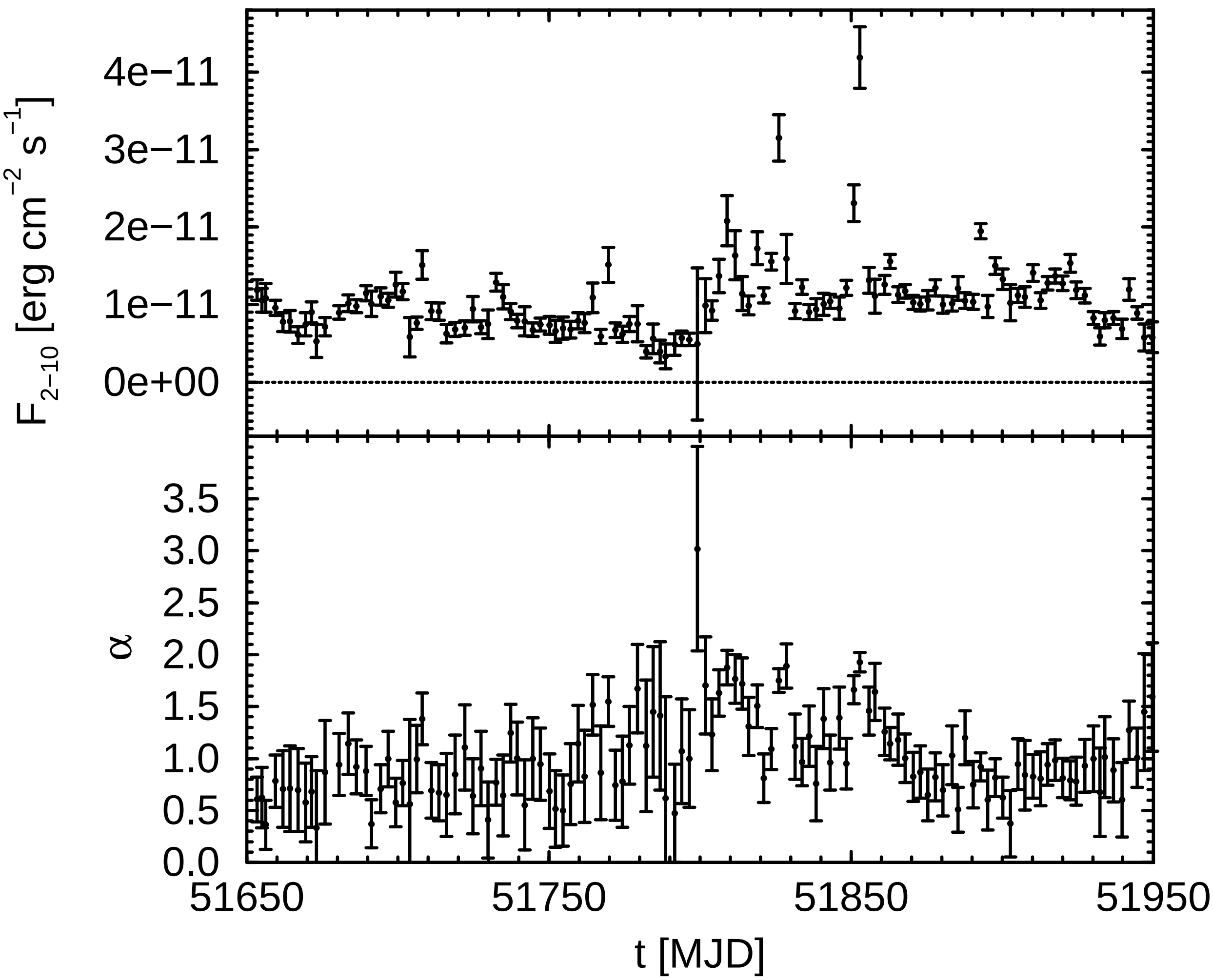

Fig. 6.— RXTE PCA flux and best-fit spectral-index history.

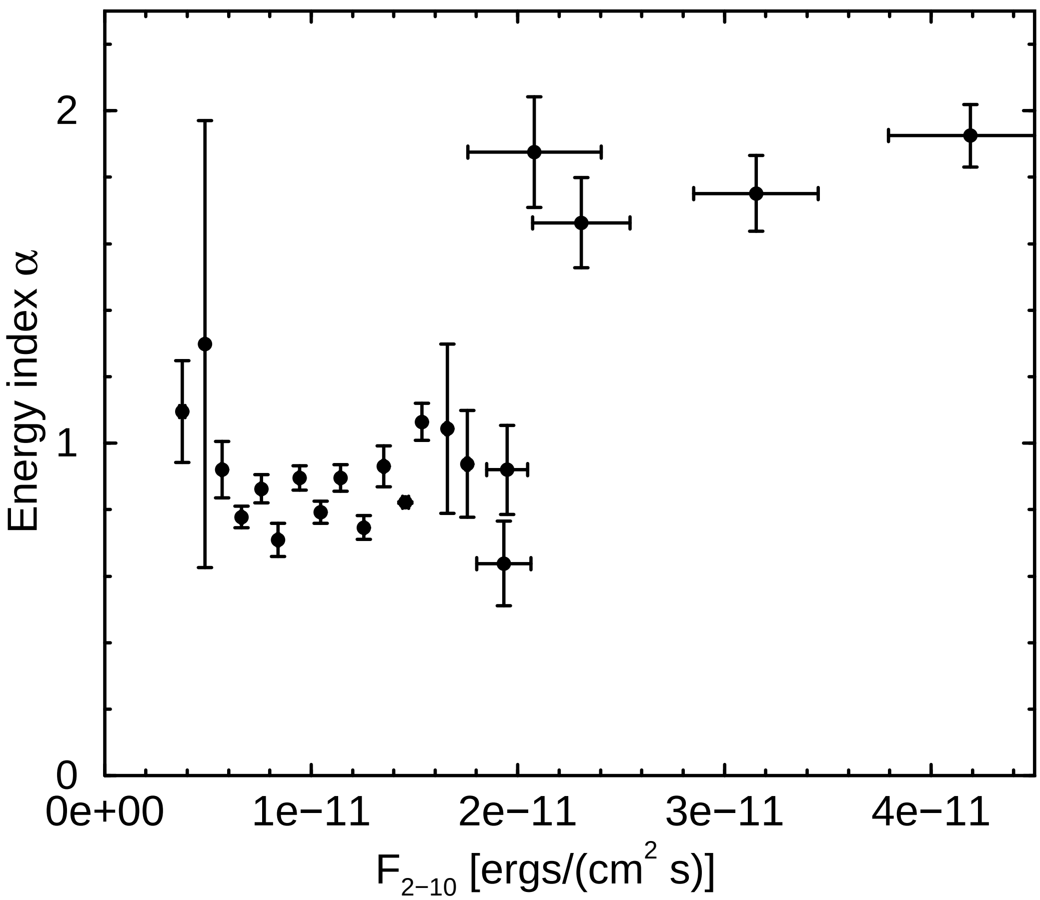

Fig. 7.— Hardness-intensity plot for the *RXTE* PCA measurements. At $F_{2-10} < 1.8 \times 10^{-11}$ ergs cm^{-2} s^{-1}, the data have been rebinned into flux bins of $\Delta F_{2-10} = 10^{-12}$ ergs cm^{-2} s^{-1}. At higher flux values, data points from individual PCA observations are displayed. High flux states are always associated with a soft spectrum, but no obvious hardness-intensity correlation is visible at low X-ray flux levels.

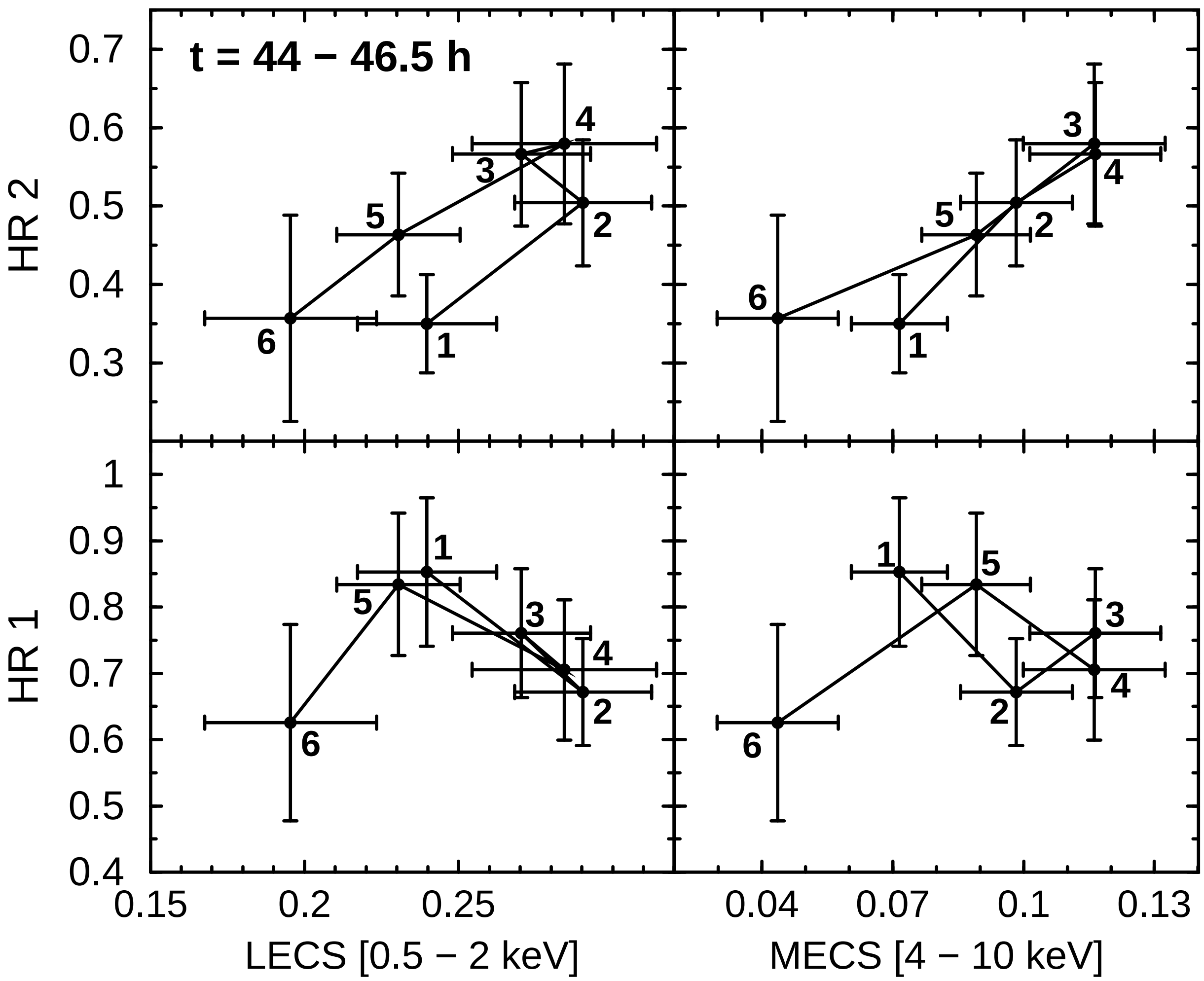

Fig. 8.— Hardness-intensity diagram of the *BeppoSAX* hardness ratios HR1 and HR2 as defined in §2.3.2 vs. soft X-ray LECS and medium-energy MECS flux for the well-resolved X-ray flare at t = 44.0 – 46.5 h (see Fig. 3).

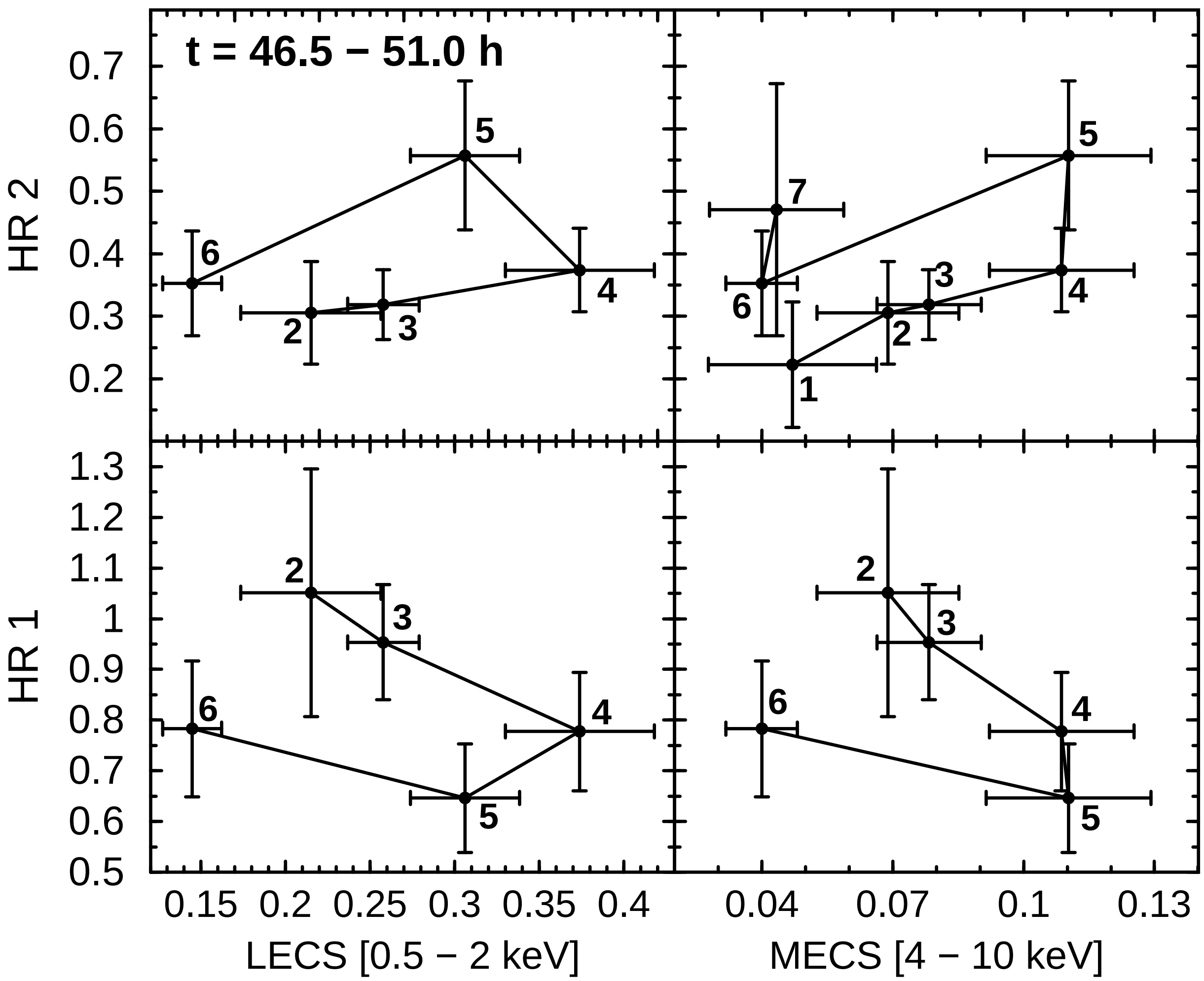

Fig. 9.— Hardness-intensity diagram of the *BeppoSAX* hardness ratios HR1 and HR2 as defined in §2.3.2 vs. soft X-ray LECS and medium-energy MECS flux for the well-resolved X-ray flare at t = 46.5 – 51.0 h (see Fig. 3).

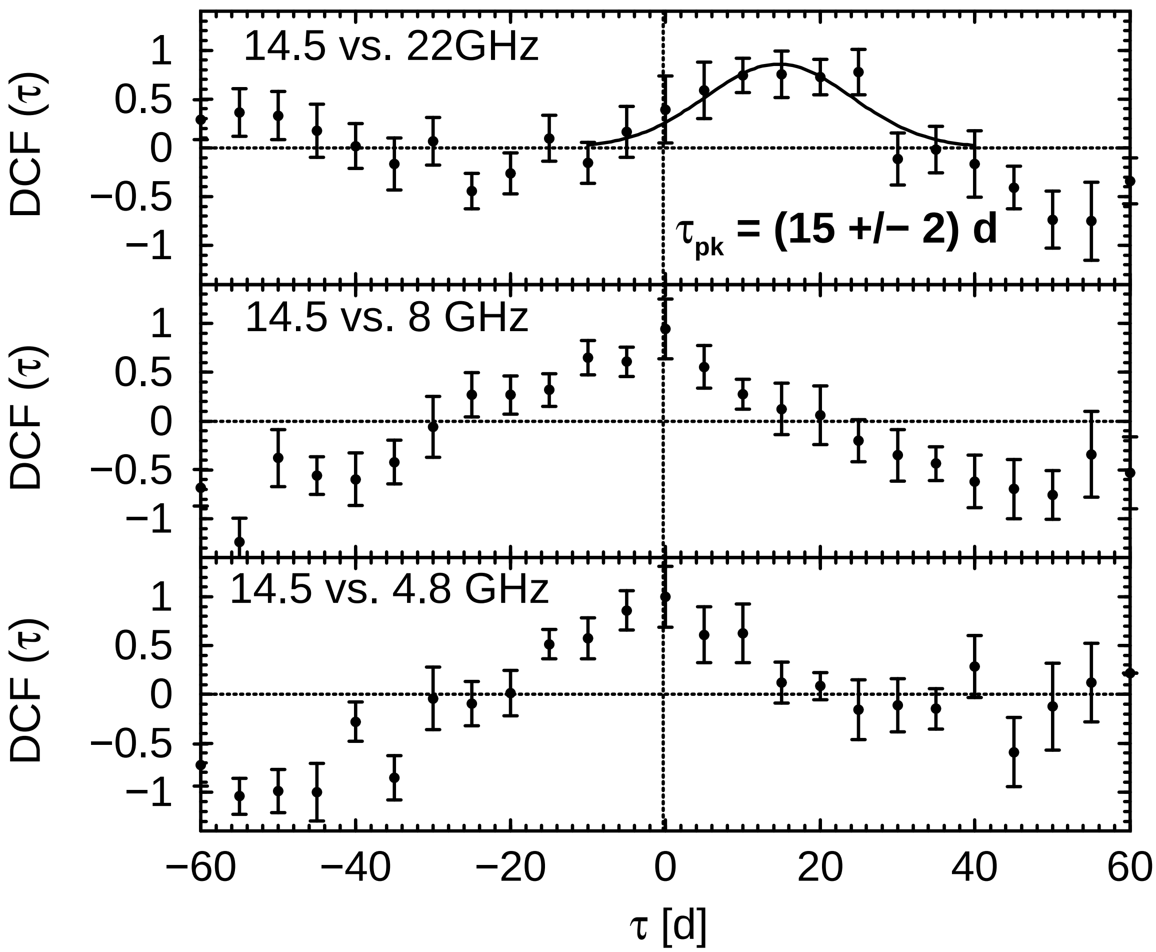

Fig. 10.— Discrete correlation functions (DCFs) between the 14.5 GHz radio light curve (the best sampled radio light curve available in our data set) with respect to light curves at other radio frequencies. The solid curve in the top panel indicates a Gaussian fit to the DCF, with $\tau_{\rm pk}$ being the best-fit offset from zero (i.e., the most likely time delay). This is only included for the 14.5 GHz vs. 22 GHz DCF since this procedure did not produce robust results (independent of the sampling time scale) for the other DCFs shown.

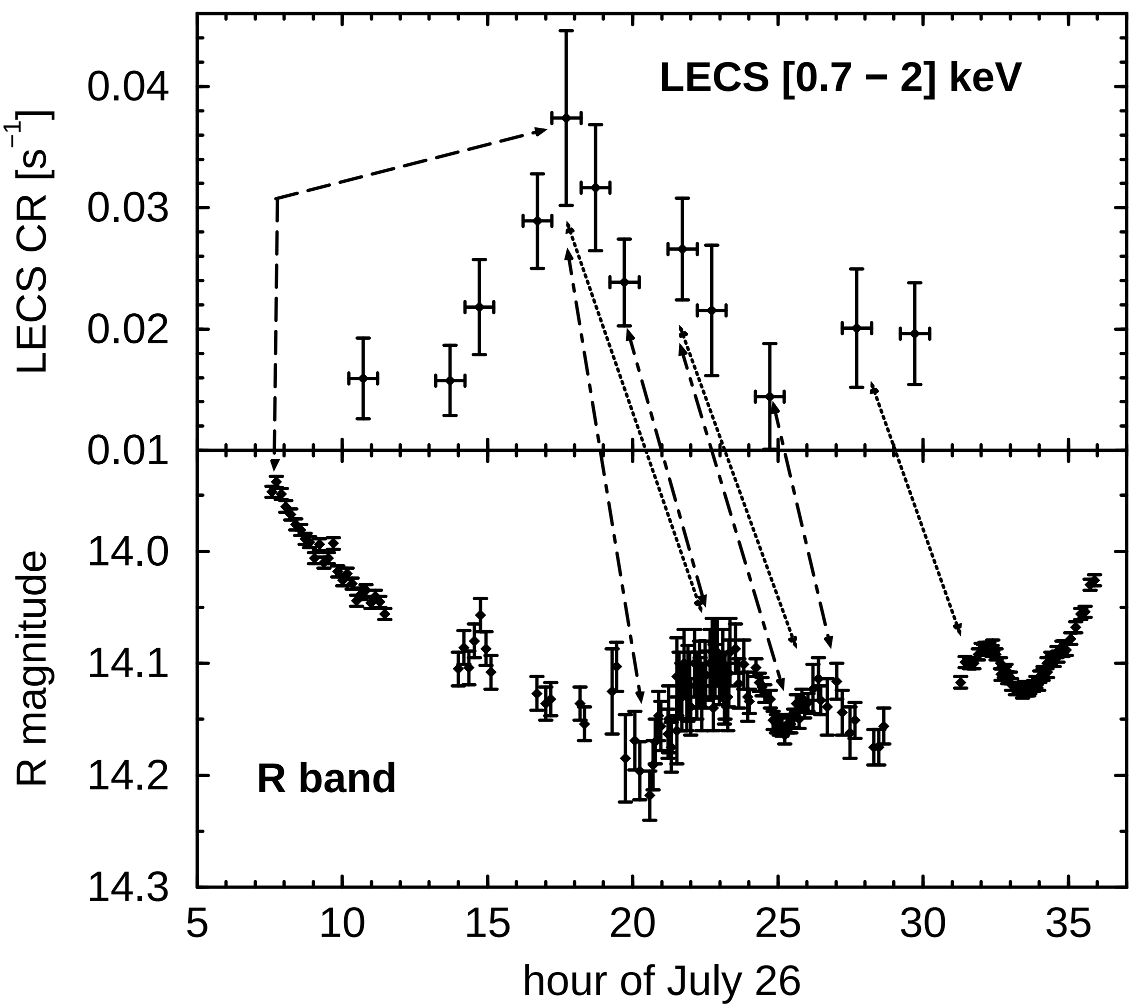

Fig. 11.— *Beppo*SAX LECS $[0.7-2]$ keV (top panel) and contemporaneous R-band (bottom panel) light curves during our first *Beppo*SAX pointing on July 26/27. The optical light curve appears to trace the X-ray light curve with a time delay of $\sim 4-5$ hr, as indicated by the dotted arrows. However, a DCF analysis (see Fig. 12) actually finds a stronger signal from an apparent anti-correlation with a time delay of ~ 3 hr, dominated by features indicated by the dot-dashed arrows as well as a strong positive correlation with an X-ray lag of ~ 9 hr behind the optical, dominated by the large optical and X-ray flares indicated by the long-dashed arrow.

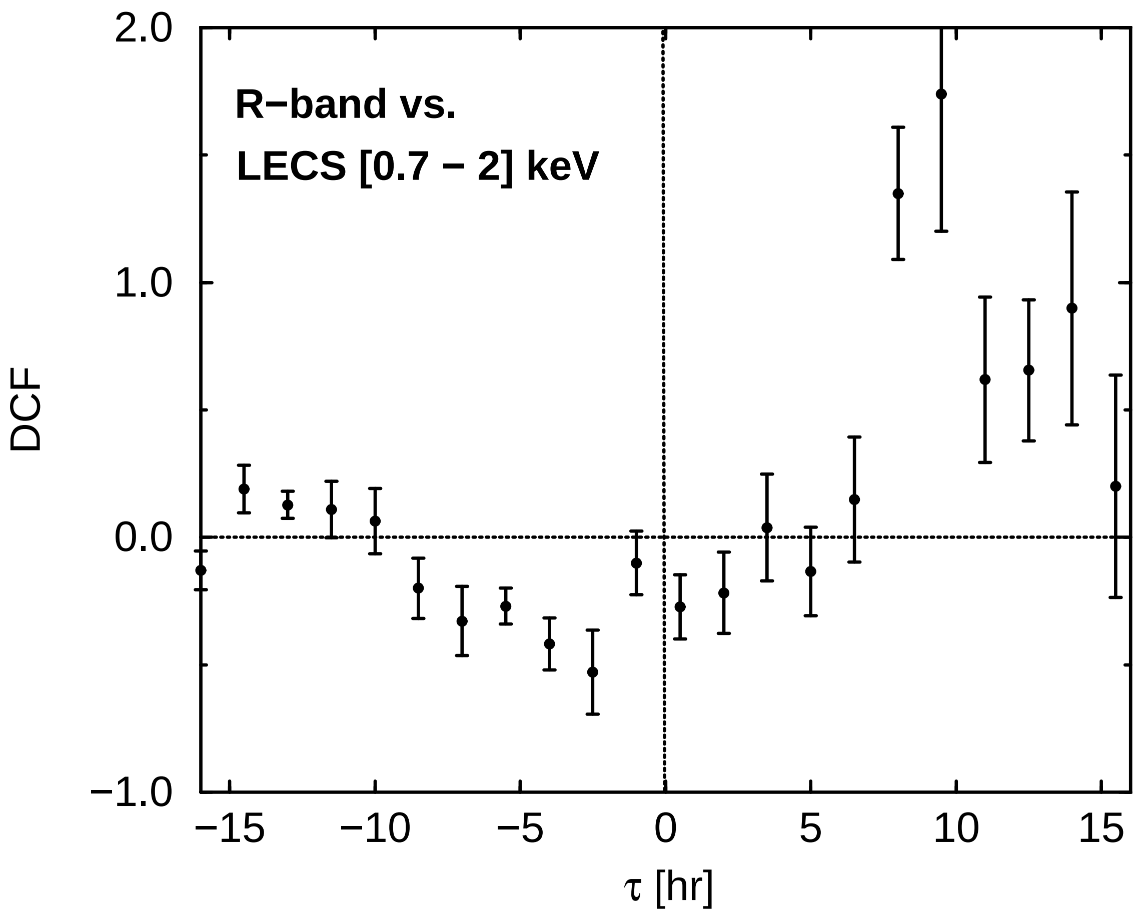

Fig. 12.— Discrete correlation function between the *Beppo*SAX LECS [0.7 − 2] keV and R-band light curves during our first *Beppo*SAX pointing on July 26/27, as shown in Fig. 11. The sampling time scale is $\Delta\tau = 1.5$ hr. The same general features are found for other sampling time scales in the range of $\sim 1 - 2$ hr.

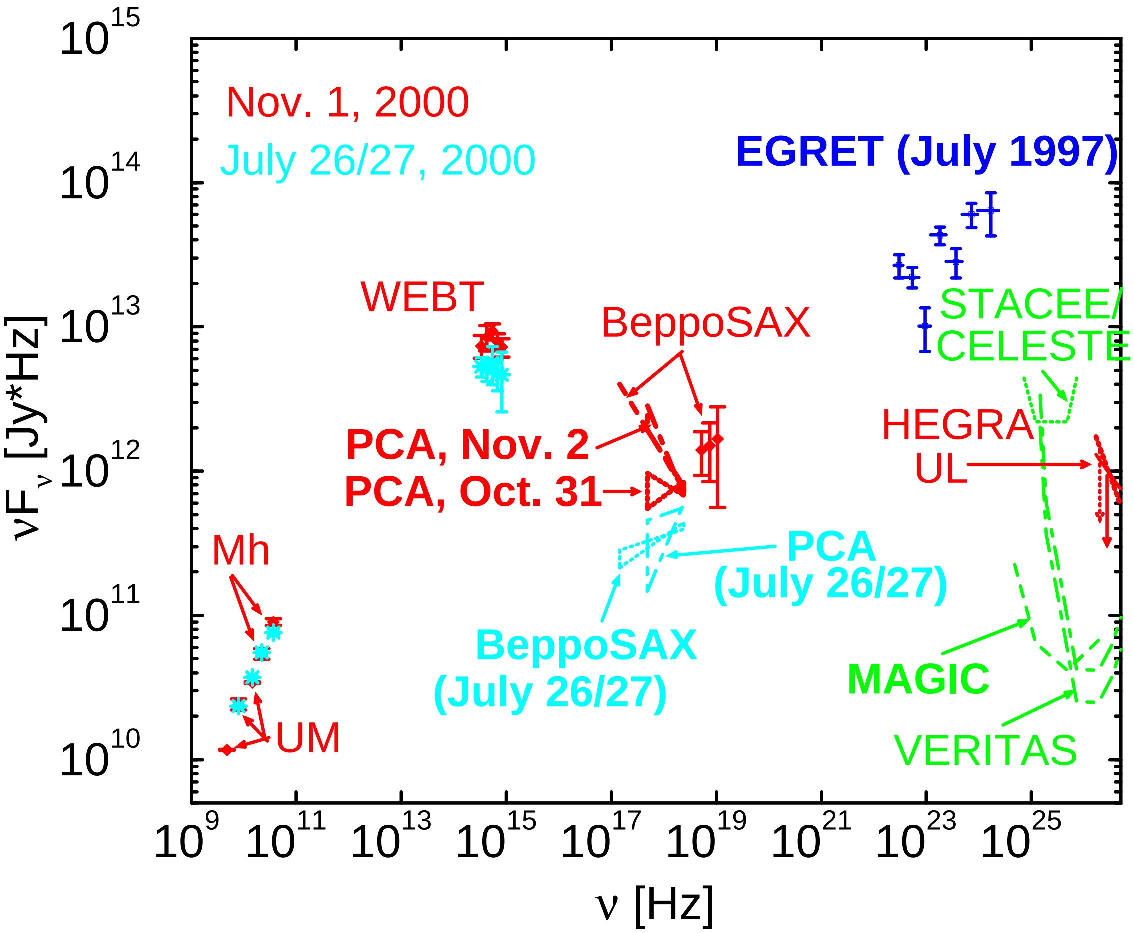

Fig. 13.— Spectral energy distributions of BL Lacertae on July 26/27, 2000 (stars; cyan in the on-line version; light grey in print), and Oct. 31 – Nov. 2, 2000 (diamonds; red in the on-line version; dark grey in print). For Oct. 31 – Nov. 2, both the PCA measurement a few hours before the *Beppo*SAX pointing, and near the end of the *Beppo*SAX pointing are included. "Mh" indicates the radio fluxes measured at Metsähovi Radio Observatory; "UM" indicates the University of Michigan Radio Observatory measurements. The two VERITAS sensitivity limits have been obtained assuming two different values of the underlying spectral index, $\alpha = 2.5$, and $\alpha = 3.5$, respectively.

Table 1. Summary of X-ray (*RXTE* PCA and *BeppoSAX* MECS) Observations and spectral analysis results for a single-power-law model with fixed $N_H = 2.5 \times 10^{21}$ cm^{-2}. The spectral analysis results for the PCA have been obtained for a fitted energy range (3 – 15) keV, the *BeppoSAX* MECS results have been obtained through MECS spectral analysis over the range (1 – 10) keV (Ravasio et al. 2003). α is the energy spectral index.

Instrument	Start time [UT]	End Time [UT]	Duration [s]	α	$F_{1\,\mathrm{keV}}$ [μJy]	$F_{2-10\,\mathrm{keV}}$ [10^{-12} ergs s^{-1} s^{-2}]	χ^2_ν/d.o.f.
PCA	July 26, 18:23:44	July 26, 19:00:32	2208	$0.9^{+0.7}_{-0.6}$	1.4	6.3	0.42 / 25
MECS	July 26, 10:12:39	July 27, 06:43:33	23309	0.8 ± 0.1	1.18	5.8	0.86 / 43
PCA	Nov. 2, 10:56:16	Nov. 2, 11:29:36	2000	$1.45^{+0.3}_{-0.25}$	10.3	19.7	0.45 / 25
MECS	Oct 31, 20:46:55	Nov. 2, 09:59:28	33661	1.6 ± 0.05	12.7	19.7	0.61 / 58